MODELLING BEAM LOSSES IN CERN'S SUPER PROTON SYNCHROTRON WITH XSUITE

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Abstract

Studies are ongoing at CERN's Super Proton Synchrotron (SPS) to understand the origin, distribution, and possible mitigations of observed beam losses. The existing equipment in the machine allows for dedicated measurements to identify bottleneck regions with higher losses. A well-suited and accurate simulation model of the SPS is indispensable to be able to study the impact of underlying beam dynamics on the loss distribution. This paper reviews the current status of the SPS model in Xsuite for loss simulations. The aperture model has recently been improved, and additional features can be enabled on demand, such as collimators and lattice non-linearities. Furthermore, the impact of the beam sagitta in bending magnets can be represented by introducing aperture offsets. This paper presents the results of the current setup, compares them to dedicated measurements, and outlines the next steps for further improvements.

INTRODUCTION

The Super Proton Synchrotron (SPS) at CERN accelerates beams up to 450 GeV. It delivers protons and ions to CERN's North Area for fixed-target experiments, and serves as the last injector for the Large Hadron Collider (LHC) [1]. As such, the reliability and performance of its operation directly impact LHC filling efficiency. Uncontrolled beam losses lead to unnecessary activation of machine elements, potential downtime, and reduced beam availability [2]. Understanding where losses occur and what drives their origin and distribution around the ring is, therefore, an operational challenge, essential both for machine protection and for identifying possible mitigations.

Loss maps, where controlled losses are generated at low intensity to assess in a safe way the beam loss distributions around the ring, are a well-established tool widely used in the LHC [3]. In the SPS, dedicated beam intercepting devices are installed but not used in standard operation. Adapting this methodology to the SPS allows identification of aperture bottlenecks, characterisation of the loss distribution, and connection to the underlying beam dynamics.

Producing meaningful loss maps requires a reliable and accurate simulation model of the machine. This paper describes the current state of the SPS model in Xsuite [4] developed for this purpose, reviews its key ingredients, and presents the first results compared to measurements conducted in dedicated machine development (MD) sessions.

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SPS MODEL IN XSUITE

Lattice and Aperture Model

The SPS model in Xsuite is built from two separate MAD-X input files: a lattice sequence and an aperture sequence. The lattice sequence was recently updated as part of the Engineering-to-Alignment (E2A) campaign [5], launched to harmonise the two main CERN accelerator geometry databases (the Layout Database (LDB) and GEODE) after the Long Shutdown 2. In particular, a systematic discrepancy in the SPS dipole lengths–where the magnetic length was treated as an arc length rather than a chord length, accumulating to a 14 mm error around the ring–was identified and corrected, along with several other element length and position inconsistencies [6]. The resulting lattice sequence is used as the basis for the model presented here.

The aperture sequence is also generated from the LDB, which contains position, type, and standardised aperture definitions for every element in the CERN accelerator complex, complemented by technical drawings, design notes and additional references. However, at present, the LDB of the SPS is not complete. Some elements have no aperture definition assigned, some have incorrect apertures due to unreported hardware replacements, and some definitions do not match the referred technical drawings. Manual checking and correction were therefore necessary to produce a usable aperture model. Anomalous loss spikes in simulations proved a useful diagnostic for this process–in one instance, unexpectedly high losses on a specific element were traced back to a chamber replacement not recorded in the LDB. Although in this process we converged to a continuous and realistic model for the full ring, the aperture model is considered a work in progress, and comparison to dedicated measurements remains an essential validation tool.

Beam Sagitta in Bending Magnets

The SPS dipoles are rectangular bending magnets (RBends), rather than sector bends (SBends) like is the case in the LHC; see Fig. 1. In an SBend, the magnet body follows the curved reference frame, such that the physical chamber is always symmetric around the reference trajectory. For an RBend, the vacuum chamber is straight, while the reference particle follows a curved arc inside it. In the present implementation of Xsuite [4], the aperture of an RBend is by default centred on the reference trajectory–a good approximation for tracking purposes, but insufficient in the context of loss studies where the exact position of the physical chamber walls matters. It is therefore necessary to explicitly shift the aperture profiles along the magnet to account for the transverse offset between the reference particle trajectory and the centre of the rectangular chamber.

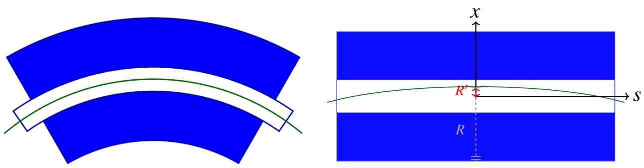

Figure 1: Illustration of SBend (left) and RBend (right).

Considering the centre of the magnet as the origin, with s_{start} the longitudinal position of the entrance of the magnet, θ the half bending angle, L the magnet length, R the bending radius and R' the transverse offset at the magnet centre with respect to the reference trajectory, the centre of the bending circle has coordinates:

$$\begin{cases} s_0 = s_{\text{start}} + \frac{L}{2} \\ x_0 = -(R - R') \end{cases} \tag{1}$$

The transverse offset of the reference trajectory at any longitudinal position s along the magnet is then given by the standard equation of a circle:

$$\begin{cases} s = R\cos\theta + s_0 \\ x = R\sin\theta - (R - R') \end{cases} \tag{2}$$

$$x = x_0 + R\sin\left(\cos^{-1}\left(\frac{s - s_0}{R}\right)\right) \tag{3}$$

Each aperture profile is shifted by the opposite of this amount at its corresponding s position. For the SPS dipoles, this results in a maximum trajectory offset of +2.2 mm at the magnet centre and −4.4 mm at the entry and exit faces [7]. Figure 2 illustrates the effect on a portion of the SPS lattice model.

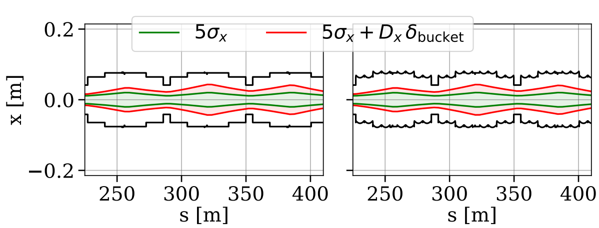

Figure 2: Aperture definition without (left) and with beam sagitta (right) for SPS dipoles.

Injection and Extraction Doglegs

SPS has an injection dogleg in the long straight section 1 (LSS1) and an extraction dogleg in LSS5. These are generated by physically shifting three specific quadrupoles for each dogleg–in the horizontal plane for the injection dogleg, and in the vertical one for the extraction dogleg [8]. To reproduce this feature in the model, the corresponding quadrupoles and their apertures were shifted by the same amount. Since shifting quadrupoles introduces a dipolar kick and hence a residual closed-orbit distortion along the machine, the orbit is corrected after the shifts are applied.

Collimators

The SPS hosts a single horizontal betatron collimator, the TCSM.51932 (1.48 m long), originally developed as a prototype for LHC collimator systems [9] and later replaced by a new prototype that features in-jaw BPMs [10]. This device is not designed for high intensities, making it unsuitable for standard LHC-type cycles, though it has been used in dedicated loss studies with single bunches [11]. The SPS also hosts an off-momentum absorber block, TIDP.11434 (4.3 m long), with a horizontal aperture of 147 mm. Its position can be adjusted to present a physical boundary ranging from −40 mm to +105 mm relative to the nominal beam position, with the asymmetric setting chosen to intercept halo particles with negative momentum offsets ($\delta < 0$) [11].

Both devices are modelled using the Everest collimator model in Xcoll [12], with carbon-fibre-carbon as the jaw material. In order to reproduce the settings during the performed measurements, the TCSM jaw gap is set symmetrically at 5σ, while the TIDP jaws are set independently in absolute position to reproduce the asymmetric opening. Both devices are optional components of the model and can be enabled or disabled depending on the study.

Lattice Non-linearities

The SPS lattice contains non-linear field errors in its magnets, which cause the betatron tunes Q_x and Q_y to become dependent on the momentum offset δ. This is particularly relevant for momentum acceptance studies, where an accurate representation of the detuning is essential. The error model was developed by fitting multipole field errors to measurements of Q_x and Q_y as a function of δ [13], under the hypothesis that all magnets of the same type receive identical errors. This results in additional sextupole and decapole components (b_3, b_5) on the dipoles and octupole and dodecapole components (b_4, b_6) on the quadrupoles, where b_n denotes the $2n$-pole field harmonic.

Since these errors are produced by field imperfections, their values are independent of the chosen working point. The tune and chromaticity can therefore be rematched to any desired values after inserting the errors into the model. Like the collimators, the non-linearities are an optional component which can be enabled or disabled depending on the requirements of the study.

LOSS MAPS DEVELOPMENT FOR SPS

Loss maps are a tool used to generate losses in a controlled way with safe beam intensities in order to determine in what elements of the ring particles are lost and identify bottlenecks. This is a well-established procedure in the LHC [3, 14], developed to assess the performance of the collimation system. The LHC has two insertion regions dedicated to collimation: one for betatron cleaning–used to intercept particles at high oscillating amplitudes–and one for off-momentum cleaning–used to remove particles with high momentum deviation before they are lost in high dispersion regions. As a consequence, there are two different types of loss maps. Betatron loss maps are performed by blowing up the beam with the transverse damper, resulting in particles reaching large amplitudes in phase-space and hence leading to a fast emittance growth. On the other hand, off-momentum loss maps are produced by changing the RF frequency [15]–a radio-frequency sweep (RF-sweep)–to give particles the required momentum deviation. An important part of collimation studies is also simulating these loss maps. Traditionally, betatron loss maps were performed with a so-called pencil beam [3] (particles are generated directly onto the primary collimator), which is very efficient in computation time. In Xsuite [12], both the ADT-style blow-up and the RF-sweep are implemented as well, allowing realistic simulations.

While the SPS does not have an extensive collimation system, loss maps are still useful to identify bottleneck locations and overall establish that the physics behind losses is understood. This is the main driver to develop this tool for other machines than the LHC. First loss measurements in the SPS were performed in 2006 after the installation of the prototype [16], but a first attempt to perform loss maps in the SPS with increased BLM gain (and hence more loss resolution) was performed in April of 2025, both for betatron and off-momentum loss maps, with both collimator devices in. This attempt showed the feasibility of performing loss maps in the SPS, although with decreased resolution compared to the LHC, because of the significantly lower beam-loss monitor (BLM) coverage of the ring. Another important difference is that betatron loss maps have to be performed through a tune chirp–modifying the tune directly to destabilise the beam–as no setup for a controlled blow-up is available in the SPS. Off-momentum loss maps are performed in the same way as in the LHC.

As a benchmark of simulation tools, the loss maps produced experimentally were also simulated in Xsuite. The comparison of measured loss maps to simulated ones is a very important step towards validating the SPS model itself. Figure 3 shows both a simulated and a measured loss map performed with the same parameters: both collimator devices in, betatron collimator jaws at 5σ and off-momentum absorber block in nominal operation condition. The machine was running the nominal Q20 optics for LHC-type beams at injection energy, the chromaticity was matched to 0.5 (normalised units), and the octupoles were off. Both measurement and simulation give comparable loss patterns: the fractions of losses on the TCSM and TIDP are strongly alike, and most of the loss clusters of the measured loss maps are reproduced by the simulated ones with similar loss values. The discrepancies can be explained by a combination of the decreased BLM resolution in SPS and the intrinsic difference between simulation, which localises losses exactly, and measurements, which are limited to BLM positions. Off-momentum loss maps were also produced using an RF-sweep and show similar promising agreement with measurements, although a detailed comparison is left for future work. However, since the betatron collimator is not used in operation, it is important to simulate a case without

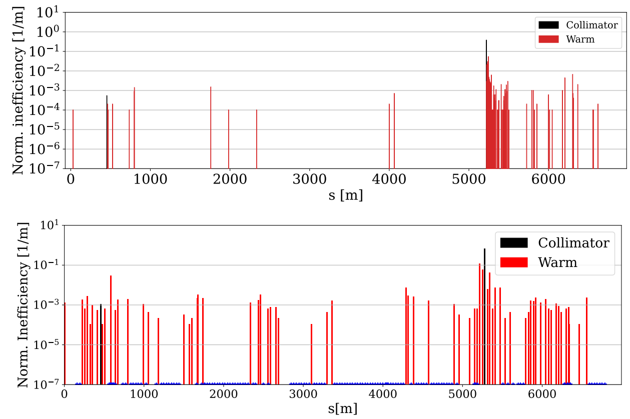

Figure 3: Simulated (upper) and experimental (lower) loss map with betatron collimator (TCSM.51932) at 5σ and off-momentum absorber block (TIDP.11434) at nominal position.

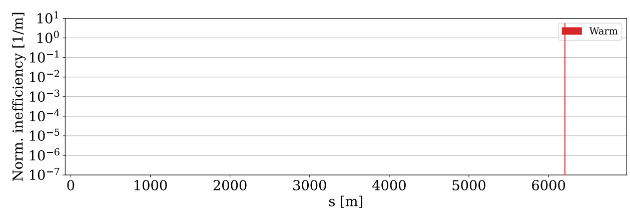

Figure 4: Betatron loss map without betatron collimator (TCSM.51932).

it as well. This is done in Fig. 4. The loss map becomes unrepresentative of reality, as all losses go to one (or a few) apertures. Indeed, when removing the betatron collimator, the primary bottlenecks become apertures, which act as black absorbers: a particle hitting an aperture will immediately be lost, while a particle hitting a collimator will be scattered over a few turns before stopping in secondary bottlenecks. This indicates the need for further development of the model to include realistic apertures that allow scattering.

CONCLUSION

The current state of the SPS model in Xsuite for loss studies has been presented. The model is built from an updated lattice sequence and an aperture model extracted from the LDB, complemented by optional components including collimators and lattice non-linearities. A dedicated treatment of the beam sagitta in the SPS rectangular bending magnets was developed and implemented as aperture offsets. The first betatron and off-momentum loss maps were produced and compared to dedicated measurements, showing promising agreement. However, in the absence of the betatron collimator, the simulated loss map becomes less representative due to the lack of scattering on beam pipes, and can only be used to confirm the global bottleneck. Future work will focus on completing and validating the aperture model and on implementing realistic pipe scattering to extend the loss map methodology to configurations without the collimators.

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